

Firmness and force relaxation characteristics of tomatoes stored intact or as slices

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Abstract

Firmness is an important aspect of the quality of fresh tomatoes. Its measurement is necessary for quality control, as well as for postharvest studies to develop procedures for preparation and handling of fresh-cut tomato slices. This study had two objectives, to determine how initial ripeness and cutting affect the textural changes in tomato tissue during storage and to develop a method for measuring textural attributes of tomato slices. Firmness and force relaxation characteristics were compared for tomato flesh harvested at six maturity stages and stored intact or as slices for 0–20 days. Measurements were made at three sites in the outer pericarp and three in columellar tissue on 7-mm thick transverse slices. Following loading, stress relaxation was recorded for 10 s. A 4-mm cylindrical probe provided more consistent firmness measurements (lower% CV) than a 6.4-mm spherical probe at harvest, and distances of 3 mm provided more consistent results than 1 mm. Therefore, stored tomato samples were tested only with the 4-mm cylindrical probe and distance of 3 mm. F_{\max} (maximum force) of freshly harvested tomatoes ranged from 15 to 2 N for mature green and red tomatoes, respectively. F_{\max} was closely related to loading energy (area), slope, and yield force; i.e. all four parameters measured elastic behavior. F_{\max} also was related ($r^2 = 0.77\text{--}0.97$) to forces at specific relaxation times. Tomatoes stored intact generally had lower CVs than those sliced before storage, although there was little difference in average firmness (F_{\max}) between the two at a given storage time for a given initial ripeness. A three-parameter model was developed to fit the relaxation curves: $Y = 1 - A \ln(1 + t) - Bt/(C + t)$ where t is relaxation time. There was little correlation between F_{\max} and the three relaxation parameters ($r^2 = 0\text{--}0.33$), i.e. the relaxation parameters measured a different physical property, presumably viscoelasticity. The responses of the relaxation parameters over storage time were dependent on the initial maturity of the tomatoes; but values usually differed significantly between tomatoes stored intact or sliced, with tomatoes sliced before storage generally having higher values, which we interpret as having lower viscoelasticity. Published by Elsevier Science B.V.

Keywords: Firmness; Force relaxation; Viscoelasticity

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1. Introduction

There is presently considerable interest in developing fresh-cut tomato slices with extended shelf life. Firmness is a critical aspect of tomato quality. Its measurement is necessary for quality control, as well as for postharvest studies to develop procedures for preparation and handling of fresh-cut tomato slices. Several approaches have been used to measure firmness of intact tomatoes based on compression, puncture, creep, or relaxation of the intact fruit. However, the texture of the flesh itself, particularly the radial and outer pericarp, needs to be measured to evaluate eating quality and for physiological studies. Although there is considerable literature on the firmness measurement of intact tomatoes, little has been published on measuring cut tissues. Ahrens et al. (1987) compared creep measurements on intact tomatoes and Kramer shear on excised pericarp tissue with sensory evaluations of firmness and mealiness. They found that tomato tissue texture was not reliably predicted by intact fruit measurements. Hall (1987) measured firmness of outer (opposite locules), radial, and inner pericarp tissues using a 4.9-mm cylindrical probe on 12.5-mm thick tomato slices. He found that the outer pericarp was generally firmer than collumella, that most softening occurred within 4 days after incipient color, and that tissue softening rates of the different tissues were cultivar dependent. Kojima et al. (1991) used a conical probe (2.1 mm diameter with a 30° apex angle) to measure force relaxation characteristics of tomato flesh for 60 s following an initial load of 5 g (2 g for ripe fruit). Sakurai and Nevins (1992) assessed tomato softening by inserting the same conical probe to a depth of 0.6 mm (total volume of 0.016 mm³) and then following relaxation for 60 s. In addition to having higher loading forces (higher elasticity), green tomatoes exhibited higher residual loads and later times when force decay (relaxation) stopped (higher viscosity). Sakurai and Nevins (1992) comment that the conical probe was developed by Kojima et al. (1991) because, flat or rounded probes generated friction which confounded the relaxation curve. They also point out that the conical probe has an advantage in the measure-

ment of a very small region within the fruit, thus avoiding tissue variation. Those two conical probe methods were intended to sample a very small volume of tissue for physiological studies, so they may not be representative of the entire fruit and they may not reflect textural attributes that relate to texture perception during eating. They also require 60 s per test, so are not practical for testing large numbers of samples. Errington et al. (1997) followed relaxation of whole tomatoes for 10 s, beginning at an initial load of 4 N. They used relaxation equations proposed by Peleg (1980) to determine an initial decay rate and the portion of initial force not relaxed at equilibrium to evaluate firmness of intact tomatoes.

A method to measure texture of tomato tissue is needed for both inspection and research on fresh-cut tomato slices. This study had two objectives, to determine how initial ripeness and cutting affect the textural changes in tomato tissue during storage and to develop a method for measuring textural attributes of tomato slices.

2. Materials and methods

2.1. Tomatoes

Tomatoes (*Lycopersicon esculentum* Mill., 'Sun-beam') were harvested in Beltsville, MD, at mature green, breaker, turning, pink, light-red, and red ripeness stages (USDA, 1975). Within a ripeness stage 120 fruit were paired visually, and the pairs were randomly assigned to six storage durations. One of each pair was sliced before storage and the other was stored intact (storage condition). A total of 720 tomatoes were used, 6 ripeness stages × 6 storage durations × 2 storage conditions × 10 tomatoes). All fruit were surface sterilized by immersion in 0.003 Ml⁻¹ NaOCl (200 ppm), pH 6.5, at 5 °C for 2 min. Fruit to be stored as slices were sliced 7 mm thick using a rotary meat slicer. Both end slices were discarded and the center four slices were stacked in 40 × 135 × 185 mm polystyrene boxes, three or four tomatoes per box, and covered with plastic film. The film was perforated ten times with a needle to ensure an aerobic atmosphere (Bai and Watada

1998, personal communication). Tomatoes to be stored intact were packaged in polyethylene bags, three or four fruit per bag, tied shut and perforated ten times. Both sliced and intact fruit were held at 5 °C for 0–20 days and storage lots were tested at ca. 4-day intervals. Just before measurement, the intact tomatoes were sliced as described for the presliced fruit.

2.2. Firmness testing

Force-deformation curves were recorded using a universal testing (force deformation) instrument (Stable Microsystems Texture Analyzer, Surrey, England, UK) loading at 1 mm s⁻¹ to a specified distance and then following stress relaxation for 10 s (Fig. 1). Force was recorded at 0.04 s intervals, thus there were 75 datapoints in loading and 251 in relaxation. Three measurements were made on each slice at a junction of outer and radial pericarp and three were made in the columella, avoiding visible vascular bundles' fissures, and locular tissue (Fig. 2).

We chose to sample relatively large tissue volumes to minimize local variations in cellular structure, thinking that such a measurement would ultimately better relate to eating experience than would measurement with a needle penetrometer, whether flat-faced or conical. Since the two subsets of tomatoes of each ripeness category were

not expected to differ on day 0, those fruit were used to compare two probes, a 4-mm diameter flat-faced cylinder and a 6.35-mm diameter sphere (Fig. 2), and two distances, 1 and 3 mm (designated Cyl-1, Cyl-3, Sph-1, and Sph-3). Rationale for probe and distance selection is discussed below. The adjacent surfaces of the two center slices from one subset were tested using the 4-mm cylinder, one slice being probed to 1 mm and the other to 3 mm. The other subset was similarly tested using the spherical probe. Based on analysis of these data, all subsequent tests were made using the 4-mm cylinder and distance of 3 mm. Only the center slice of each tomato, the slice with greatest diameter, was used for subsequent tests.

The probes were selected to have diameters less than the width of the pericarp but large enough to sample representative volumes of tissue. Flat-faced cylindrical probes are generally preferable for flat specimens such as slices, but curved probe surfaces make slight irregularities in the sample surface less critical and are preferred for generally spherical items such as intact tomatoes. A cylindrical probe is easier to machine precisely and is therefore more transferable among laboratories with different force-deformation instruments. Additionally, cross-sectional area is constant for a cylinder, whereas area increases with depth for a spherical probe until the depth equals the radius, magnifying any error in depth control. Of course, pressure distribution patterns differ considerably between spherical and flat probes (Mohsenin 1986), with a flat punch exerting greater pressure at the perimeter and the sphere, at center. The distances were selected after preliminary trials indicated that 3.5 mm (50% of slice thickness) tended to cause tearing at the corners of the locules at the pericarp sites, but 3 mm did not. We selected 1 mm as a minimal depth to sample a reasonable volume of tissue. The 10-s relaxation time was selected for both experimental and practical reasons. To be practical for routine testing, a test needs to be as quick as possible without sacrificing the characteristic of interest. (More than 4000 measurements were planned for this study alone.) A survey of the literature indicated that intact-tomato creep or relaxation tests of 5–15 s had been reported. Kojima et al. (1991)

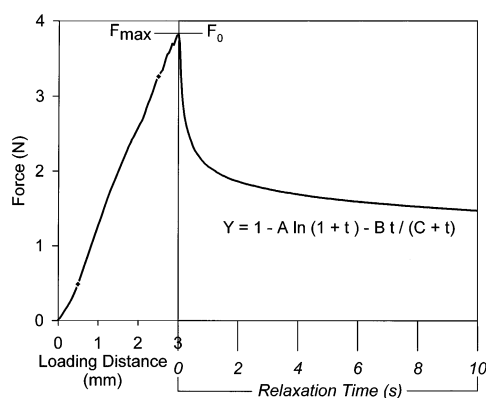


Fig. 1. Typical force relaxation curve for 7-mm tomato slice using a 4-mm diameter cylindrical probe loading to 3 mm deformation at 1 mm s⁻¹ and then maintaining that deformation for 10 s.



Fig. 2. Location of punches on tomato slice (upper) and 6.35-mm spherical probe (lower left) and 4-mm flat-faced cylindrical probe (right) (both diameters).

and Sakurai and Nevins (1992) measured relaxation of tomato tissue for 60 s and did not achieve complete relaxation. Our preliminary tests showed that relaxation curves tended to level off to a considerable extent after 10 s and that the curve could be modeled with only about 10 s data. Using the 10-s relaxation time, positioning and actual measurement averaged nearly a minute per site.

The forces and distances at the initial peak or bioyield (F_{yield} and D_{Fyield}) and at maximum force (F_{max} and D_{Fmax}), total area (energy), and slope were extracted from the loading portion of the curve. Mohsenin (1986) defined bioyield as a decrease or no change in force with increasing deformation, occurring before rupture. After inspection of the curves, we chose to define bioyield for automated data extraction as a drop in force of >0.05 N. Slope of the loading curve was determined by regression between 0.5 and 2.5 mm to avoid the possible nonlinear initial portion of the curve and the occasional bioyield. F_{max} , the force at 3.0 mm, the termination of the loading phase, was taken as the initial force F_0 for relaxation. Since the decrease in force after a specified relaxation time is often reported in the literature as an indication of intact tomato firmness, differences in forces from F_0 to selected relaxation times were calculated (ΔF_t , where t is relaxation time). Specific times (0.5, 1, 3, 5, and 10 s) were chosen to encompass creep or relaxation times reported in the literature and to test whether shorter relaxation times could be used in routine testing. The relaxation curves were then normalized by dividing each curve by its initial value (F_0) and various models, including exponential, rational, logarithmic, and the equations proposed by Peleg (1980) and Kojima et al. (1991) were tested to fit the shapes of the relaxation curves.

3. Results and discussion

3.1. Measurement method and parameters

Since F_{max} is the force/deformation measurement most commonly used in horticultural firmness tests, we compared the alternative measurements to F_{max} using the 0-day data. F_{max}

Table 1

Comparison of two probes and two distances for measuring 7-mm slices of tomato: F_{max} means for various ripeness stages on the day of harvest and CV from ANOVA

Ripeness	Mean F_{max}			
	1 mm		3 mm	
	Sphere	Cylinder	Sphere	Cylinder
Mature green	4.36 a	7.28 a	19.87 a	15.03 a
Breaker	4.01 a	5.91 b	15.92 b	12.23 b
Turning	2.88 b	4.92 c	11.84 c	10.99 b
Pink	1.50 c	2.97 d	6.01 d	7.19 c
Light-red	1.05 cd	1.59 e	3.63 de	3.04 d
Red	0.68 d	1.00 e	2.42 e	2.19 d
MSD ^a	0.79	0.92	2.61	1.97
CV (%) ^b	23.87	15.49	16.94	14.12

^a MSD minimum significant difference for Scheffe's test, $P < 0.05$; within a column, means followed by the same letter are not significantly different.

^b CV = coefficient of variation.

was identical to F_{yield} for both probes at the 1-mm distance. In the 3-mm tests, bioyield seldom occurred and then only in the green and breaker stages; and it occurred very close to maximum loading, always >2.5 mm. In most slices, bioyield was indistinguishable from F_{max} (as indicated by the close relationship between F_{max} and F_{yield} , Table 2), in which case F_{max} was used as the F_{yield} value. Additionally, F_{max} was closely related ($r^2 > 0.96$) to area, slope, and F_{yield} within all four tests; so only F_{max} will be discussed for the loading portion of the curves. F_{max} from Cyl-3 was closely related to F_{max} from Cyl-1 ($r^2 = 0.91^{**}$) and from Sph-1 ($r^2 = 0.91^{**}$); the relationship was lower with F_{max} from Sph-3 ($r^2 = 0.78^{**}$).

The average F_{max} for all four test methods (probes and distances) decreased as expected with increasing ripeness stages (Table 1). The four methods differed slightly in sensitivity to ripeness as shown by the number of means indicated as significantly different by the Scheffé test (Table 1). The CV from Cyl-3 was lowest and that for Sph-1 was highest. Therefore, based on the precision and on convenience, we decided to use only the cylinder to the 3 mm depth for poststorage measurements.

No model with two parameters fit the relaxation curves very well. Coefficients of determination from nonlinear regression were $R^2_{\text{nl}} < 0.97$, and there were visible differences between actual and computed curves. For example, the equation proposed by Peleg (1980) did not fit the transition between the early rapid decay and the portion approaching equilibrium particularly well (Fig. 3, $R^2_{\text{nl}} < 0.97$). Based on fit (R^2_{nl}) and simplicity (fewest parameters), the following equation was chosen:

$$Y = 1 - A \ln(1 + t) - Bt/(C + t) \quad (1)$$

where Y was normalized force; t was relaxation time with $0 \leq t \leq 10$; and parameters A , B , and C were coefficients of nonlinear regression (Fig. 3) [Proc NLIN from SAS (1989)]. Note that this is an empirical equation, based on statistical fit of the data rather than on a rheological model. For ripeness groups from mature green to red, the R^2_{nl} s for our model were ≥ 0.983 . Fig. 3 demonstrates the effects of A , B and C on the normalized curve shape. An increase in A causes longer, more extensive decay in force, so A is related to overall viscoelasticity of the samples with larger values being less viscous. Increasing B results in a downward shift in the relaxation curve but does not alter the overall slope beyond the initial portion, suggesting that the elastic response tends to decrease as B increases. Parameter B likely relates to equilibrium stress in rheological

models. C affects the rate of change (radius of curvature in the stress/time curve) during the initial response to stress. C , then, indicates quickness of relaxation; whereas A and B indicate extent of relaxation.

There was close correlation among the force-related values from the loading (F_{max} , F_{yield} , area, and slope) and relaxation (ΔF_t values) portions of the curve; but those were not correlated with the three relaxation curve-shape parameters (A , B , and C) at the six ripeness stages (Table 2). This suggests that the force-related measurements all provide essentially the same information about firmness or elasticity and the three relaxation shape parameters reflect a different characteristic, viscoelasticity. Therefore, the following treatment comparisons were concentrated on F_{max} and the three relaxation parameters.

3.2. Sliced versus intact

F_{max} differed between intact and sliced fruit only for Green at > 3 days, Turning at 16 days, and Pink at 11 and 20 days. In other words, there was no consistent change in F_{max} due to slicing except for the green fruit. For green fruit, curve parameter A was higher for intact fruit than for slices, but A was higher for sliced fruit at all other ripeness stages. B differed between sliced and intact fruit only at the riper stages, light-red, and red. Relaxation parameter C was higher for sliced

Table 2

Coefficients of determination (r^2)^a between F_{max} and other loading and relaxation parameters and coefficients of variation for each

Ripeness	Loading measurements			Force (N) at specified relaxation curve coefficients				Relaxation time		
	Area	Slope	F_{yield} (N)	$t = 1$	$t = 3$	$t = 5$	$t = 10$	A	B	C
Green	0.956	0.922	0.994	0.874	0.891	0.922	0.927	0.000 ns	0.000 ns	0.001 ns
Breaker	0.870	0.769	0.980	0.771	0.801	0.846	0.859	0.078	0.001 ns	0.029
Turning	0.918	0.839	0.988	0.903	0.924	0.945	0.949	0.001 ns	0.065	0.002 ns
Pink	0.924	0.843	0.992	0.885	0.904	0.939	0.947	0.178	0.083	0.107
Light-red	0.922	0.848	0.988	0.912	0.918	0.918	0.922	0.086	0.000 ns	0.334
Red	0.914	0.826	0.986	0.922	0.931	0.949	0.953	0.000 ns	0.000 ns	0.100
Total	0.980	0.960	0.998	0.953	0.960	0.968	0.968	0.020	0.091	0.169
CV(%) ^b	13.48	14.16	14.15	14.78	14.78	14.28	14.270	14.23	8.820	15.75

^a Significant at $P < 0.05$ except ns = nonsignificant.

^b CV (%) was obtained from ANOVA, where model = ripeness + tomato (ripeness).

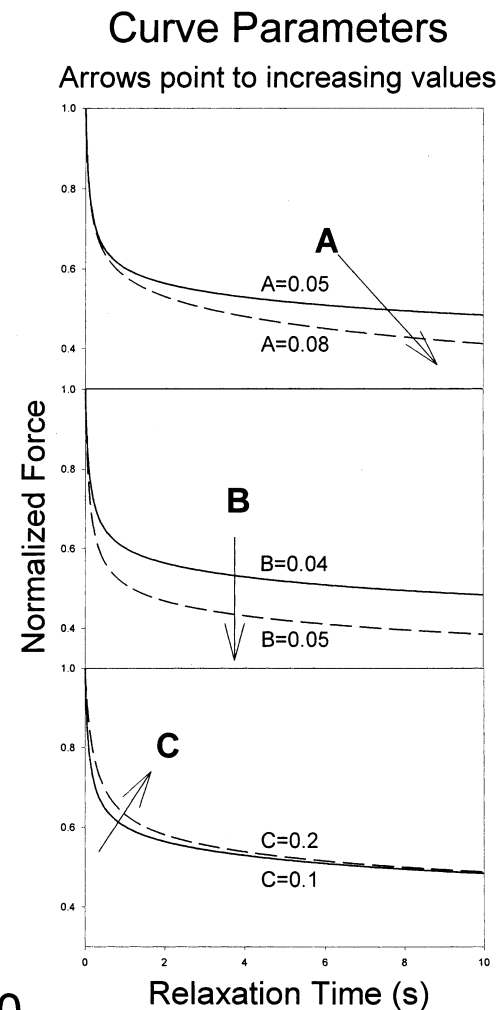
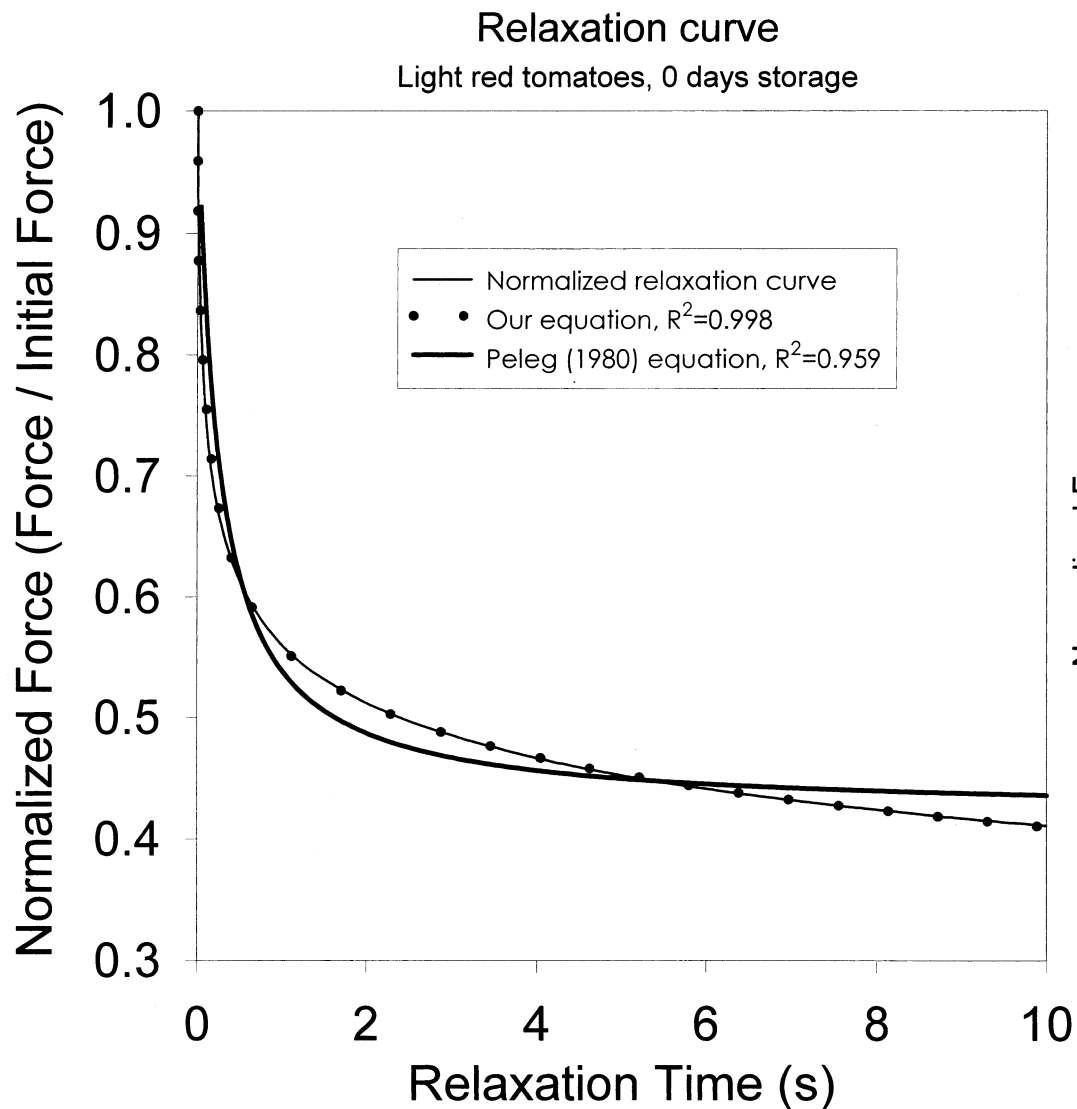


Fig. 3. Actual and computed relaxation curves for a light-red tomato and effects of increasing (direction of arrows) values for three relaxation equation parameters A , B , and C in our equation, $Y = 1 - A \ln(1 + t) - Bt/(C + t)$. Note that there are three curves in the main figure, the normalized curve from an actual tomato (thin solid line) and the curves calculated from our equation (dotted) and Peleg's equation (heavy solid line) using data from that tomato.

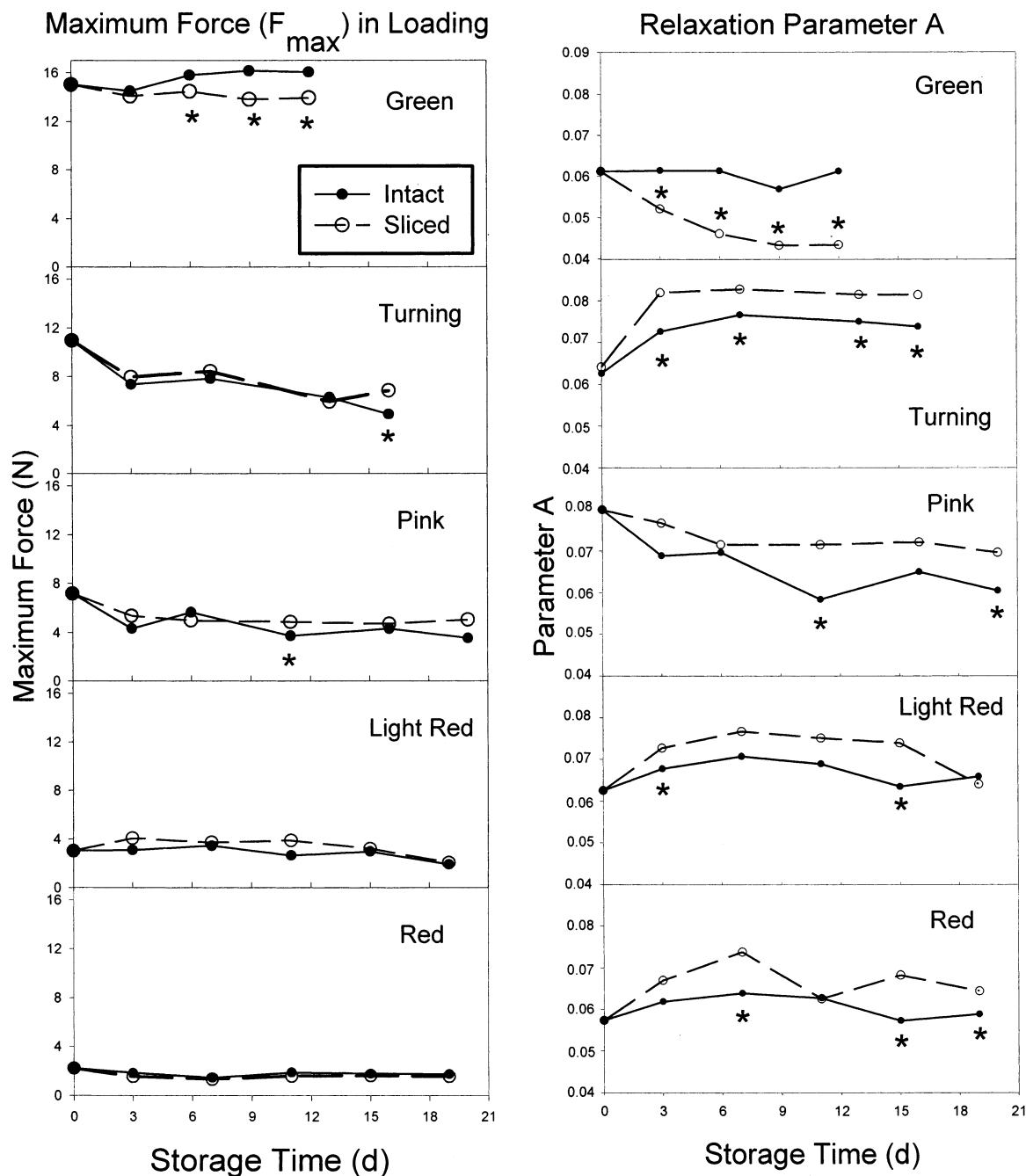


Fig. 4. Effects of initial ripeness and storage time on maximum force (F_{\max}) and relaxation curve parameters A , B , and C . *, indicates significant ($P < 0.05$) difference between values for intact and sliced tomatoes.

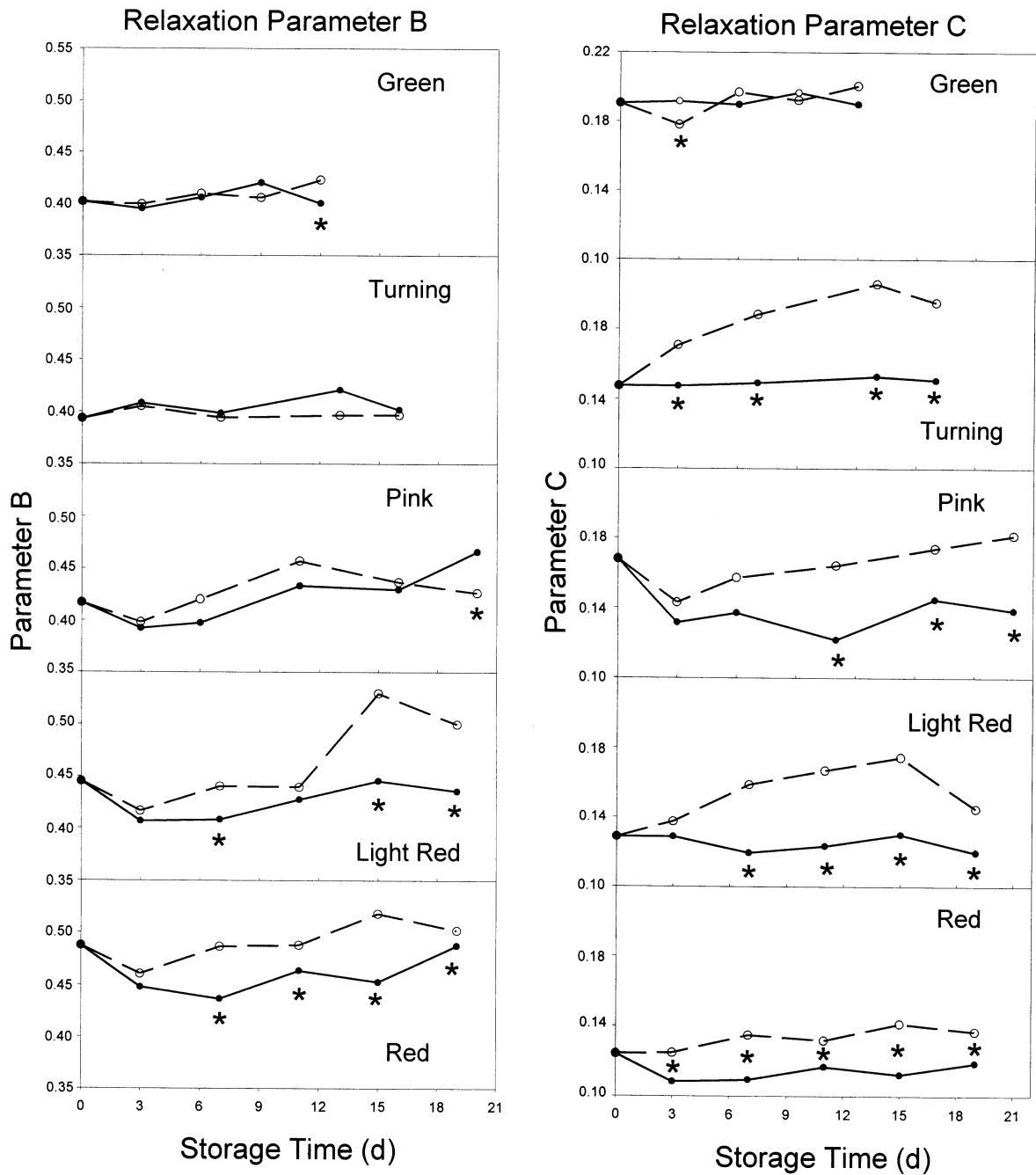


Fig. 4. (Continued)

fruit at all stages except green, where it did not differ. For tomatoes showing red color, intact tomatoes generally had lower A , B , and C values than pre-sliced tomatoes, showing quicker termination of relaxation and higher final force values. This indicates that intact tomatoes were more viscoelastic, which might be perceived orally as stiffer, firmer, or tougher; but this must be determined by sensory evaluations by trained panelists.

3.3. Storage days

For a given initial ripeness, there was little change in F_{\max} over storage days for either sliced or intact storage. Fig. 4 shows the changes in each measurement over storage for five ripeness stages. The breaker stage is omitted because it was intermediate between green and turning and because the breaker stage is very brief so we had incomplete sampling. In most cases, more variation was detected in sliced than in intact fruit, indicating slicing caused changes in both firmness and viscoelasticity over storage. Parameter A was not related to ripening, whereas B and C were related to ripening, with $R^2 = 0.76$ and 0.61 , respectively. Fig. 4 (left column) shows that there was no significant difference in F_{\max} between intact and sliced storage, except 6, 9 and 15 days on green, 17 days for turning, and 11 days on pink. It demonstrates that slicing caused little change in firmness in 2–3 weeks storage.

The changes in the three relaxation parameters over storage are also shown in Fig. 4. More significant differences between intact and sliced samples, indicated by asterisks in the plots, were detected in these parameters than in F_{\max} . Sliced fruit showed more variation over storage days than intact (data not shown). Parameter A was generally higher for sliced fruit than for intact tomatoes, with the exception of green fruit. Parameter B differed between sliced and intact fruit only for light-red and red fruit, indicating that sliced tomatoes were less viscoelastic than intact fruit in the riper stages. Parameter C was consistently higher for sliced tomatoes than for intact, except for mature green fruit. Further research is required to determine the

implications of this finding to sensory quality and functional behavior of tomato slices.

4. Conclusions

1 F_{\max} , slope, area, and F_{yield} in loading gave essentially the same information on firmness (elasticity), so reporting only F_{\max} is adequate to express the elastic changes in tomato fruit. Based on precision, the best elastic measurement for 7-mm slices, among those we compared, was provided by the 4-mm cylinder to a depth of 3 mm.

2 The relaxation curve could be described by the empirical equation $Y = 1 - A \ln(1 + t) - Bt/(C + t)$, and analysis of the parameters in the equation could detect changes in viscoelasticity due to initial ripeness stage, slicing, and storage time.

3 Our results clearly indicate that viscoelastic characteristics of tomatoes change during storage as a result of slicing and that measuring only F_{\max} or other elastic properties is inadequate to detect these changes.

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